SHORT COMMUNICATION

Scottish Landform Examples 43: Glacifluvial Landforms of Strathallan, Perthshire

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Introduction

A wide range of landforms and sediments is created by the melting of glacier ice, and commonly constitute the most prominent evidence of former glaciation. In upland landscapes, the concentration of meltwater activity in valley settings results in the development of complex assemblages of ice-contact glacifluvial erosional and depositional forms. An excellent example of such an assemblage exists in Strathallan and the tributary River Knaik, documenting the intensity and changing nature of ice-contact glacifluvial processes during the recession of the last British–Irish Ice Sheet into the Highlands of Scotland.

Brief Overview of Ice-Contact Glacifluvial Landform Assemblages

The downwasting and recession of ice sheets into mountain valleys commonly results in the accumulation of large swaths of ice-contact glacifluvial sands and gravels due to the concentration of meltwater activity in such topographic settings. This meltwater is derived from increasing rates of ice melt and the concomitant development of increasingly complex and expanding supraglacial, englacial and subglacial channel networks in what is termed 'glacier karst' (Clayton 1964; Price 1969; Boulton & Eyles 1979; Evans 2003, 2013; Bennett & Evans 2012). If meltwater cannot penetrate easily to the subglacial environment, for example, due to the glacier being largely frozen to its bed during the melt season, then supraglacial streams will flow towards the ice margin and drain along it, incising the adjacent slope and thereby developing a channel in either sediment and/or bedrock (Dyke 1993; Syverson & Mickelson 2009; Figure 1).

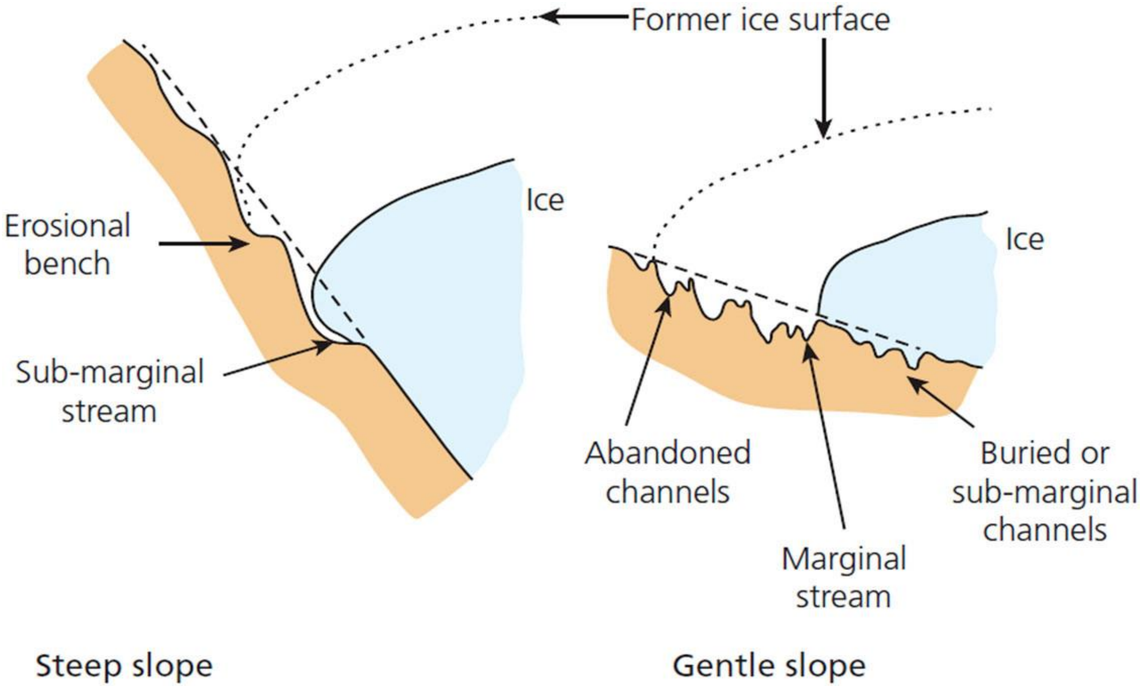

Figure 1. Conceptual model of the development of meltwater channels at the margins of glaciers in which drainage does not penetrate to the bed (after Maag 1969). Two scenarios are presented to reflect the effect of slope angle, so that a bench rather than a channel is created on steeper slopes. Note also that meltwater may descend below the glacier margin to produce sub-marginal channels, a process that can develop further if glacier basal temperatures change from cold to temperate over time.

The former pathways of glacial meltwater are often easy to reconstruct in a deglaciated landscape because they are delineated by either channels eroded by the water (Mannerfelt 1949; Sissons 1960, 1961; Dyke 1993) or the variously shaped concentrations of debris that filled the ice-walled tunnels, caverns, cavities and ponds, collectively known as 'eskers', 'kame and kettle topography' and 'ice-walled lake plains' or 'kame plateaux' (Rich 1943; Cook 1946; Price 1969; Warren & Ashley 1994; Thomas & Montague 1997; Clayton et al. 2008; Livingstone et al. 2010a, 2010b; Storrar et al. 2015; Figure 2), all of which occur in juxtaposition in areas where glacial meltwater activity was concentrated and melting out englacial debris was in abundant supply. In addition, 'kame terraces' markthe former positions of ice-marginal river beds and hence tend to appear terrace-like immediately after their initial formation but, because they contain a large amount of glacier ice, will undergo widespread collapse due to melt out (McKenzie 1969). This results in terrace fragments which display accordant surfaces when viewed from a distance. Internally, glacifluvial landforms comprise sands and gravels and minor diamicton and lacustrine components that display a wide variety of sorting, stratification, interbedding, faulting and folding, which are singly and in combination indicative of the highly variable meltwater discharges of glacial systems as well as the spatially and temporally changing morphologies of glacier karst networks and the impact of melting buried glacier ice.

Glacifluvial Landforms of Strathallan

At the close of the last (Devensian) glaciation, the recession of the ice sheet over the Forth drainage basin was characterized by the development of valley-confined glacier lobes, one of which occupied the Strathallan valley (Figure 3), forcing meltwater to drain eastwards, in the opposite direction to the modern drainage direction of the Allan Water, which now flows westwards into the River Forth north of Stirling (Sissons 1961; Forsyth 1970; Francis et al. 1970). This glacially directed, eastward flowing meltwater was responsible for the incision of the large gorge of Kincardine Glen (Aitken & Shaw 1983), which now carries the runoff from the Glen Eagles drainage basin in the Ruthven Water towards Strathearn.

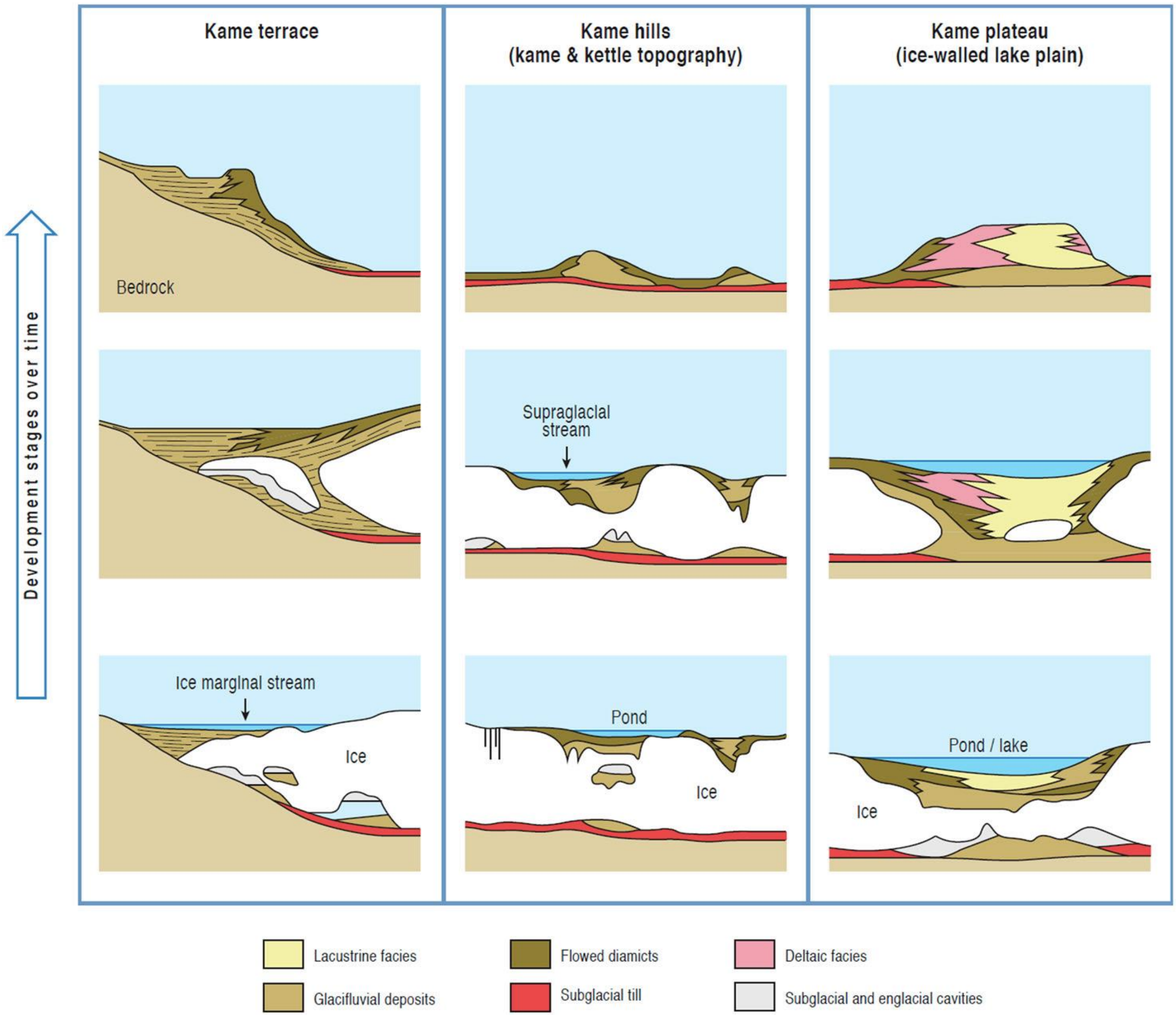

Figure 2. Genetic models of the development of the various types of kame and their relationships with ice-walled channel and tunnel infills or eskers (after Brodzikowski & van Loon 1991).

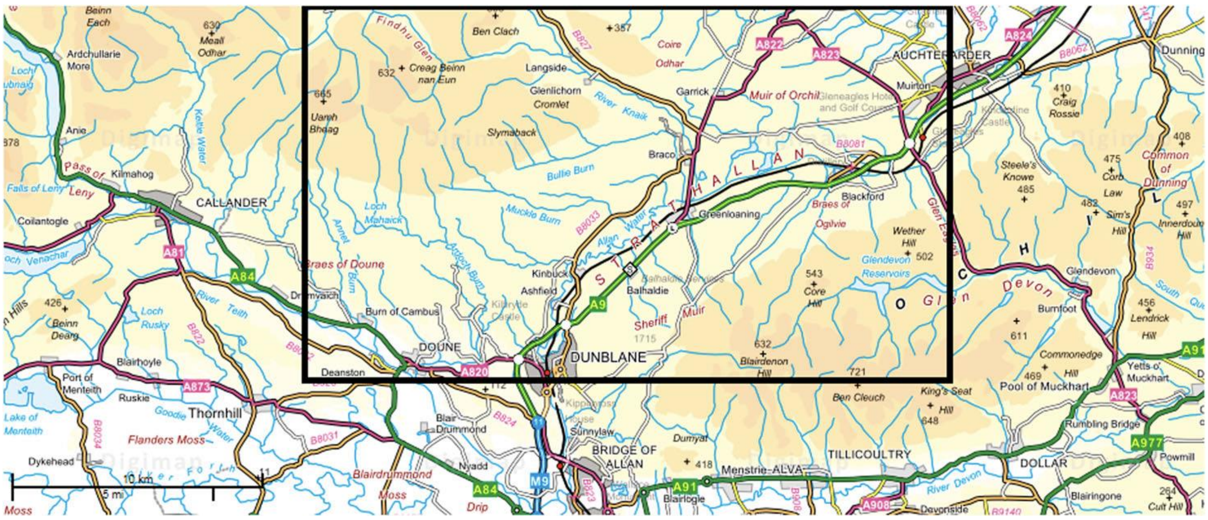

Figure 3. Location map of the Strathallan area (source EDINA Digimap), showing area covered in Figure 9 demarcated by black box. This is published under the EDINA agreement with academic institutions, specifically with Durham University, which allows use of data in academic publications.

The most renowned of the glacifluvial deposits in Strathallan are those of the Gleneagles golf course near Auchterarder, where extensive sand-rich hummocks and eskers in particular are used by Price (2002) to classify them as ‘esker and kame, parkland type’ course. Price (2002) also comments on the tendency for individual fairways to be bounded by esker ridges so that the golfer may feel that they are playing on their own private course. These landforms lie at the eastern extremity of an association of depositional and erosional features that document the concentration of meltwater activity around the receding snout of the Strathallan glacier lobe (Sissons 1961; Francis et al. 1970; Aitken & Shaw 1983) and are well represented on the British Geological Survey, Stirling drift map, sheet number 39. The glacifluvial deposits are of such significant thickness that they have been assessed in detail by Aitken and Shaw (1983) in the British Geological Survey Mineral Assessment Report 132. The unusual thickness of glacifluvial sands and gravels in Strathallan was attributed by Aitken and Shaw (1983) to the large amounts of incision and removal of valley-side drift by the densely spaced and extensive meltwater channels on the mid slopes of the valley. They also highlighted the role of Kincardine Glen in controlling the water levels in the downwasting ice to the west, which is manifest in the falling surface altitudes of incised flat-topped kames between Braco and the glen, some of which also lie above the altitude the Strathallan/Strathearn watershed at 126 m OD. The later stages of ice recession out of Strathallan towards the west gave rise to the damming of a lake in the valley floor by the glacier margin when it stood at a gravel ridge near Kinbuck (Aitken & Shaw 1983). The evidence for this lake comprises 30 m thick deposits of glacilacustrine clays lying below modern floodplain alluvium to the south of Braco.

Erosional Landforms

Glacial meltwater erosion is clearly manifest along the valley sides of Strathallan in the form of inset relict channels that descend the slopes at oblique rather than right angles to the contours, as would be normal for fluvial stream development (Figure 4). They are inset within one another or form what is called an en echelon pattern, which indicates their sequential incision in a downslope direction but guided by the former glacier margin as it downwasted (Mannerfelt 1949). The meltwater channels on the southern slopes of Strathallan were first documented by Sissons (1961) who explained them as mostly ice-marginal in origin and hence demarcating the sequential recession of an ice lobe towards the west. The occasional changes in orientation of these channels from shallow, almost contour parallel gradients to much steeper downslope gradients were identified by Sissons (1961) and interpreted by him as the products of changing meltwater flow patterns; ice-marginal directed water flow created the oblique, lateral meltwater channels but the plunging of water down chutes to form sub-marginal drainage created the downslope orientated channels. In places oblique channels turn abruptly into chutes and sometimes back to oblique angles again, indicative of marginal water plunging down sub-marginal tunnels.

Depositional Landforms

The lateral meltwater channels on the mid to lower slopes of Strathallan give way to glacifluvial sands and gravels on the valley floor, predominantly below an altitude of around 400 m OD. Ribbons of glacifluvial deposits also fill the tributary valleys of the River Knaik, Orchill Burn and Glen Eagles up to altitudes of 800 m OD. The thicknesses and extents of glacifluvial sand and gravel generally decline from a narrow valley floor fill of <18 m thickness in the west up to blankets of <25 m thickness in the east, where an esker complex forms the topography of the Gleaneagles golf course (Figure 5). Towards the edges of the main valley the glacifluvial deposits form predominantly flat-topped but locally heavily pitted terraces, where the more advanced stages of meltwater sedimentation created kame terraces. The juxtaposition of kame terraces, complex esker networks and flattopped, conical and hummocky kames documents the development of a glacier karst in the downwasting Strathallan glacier lobe (Figure 2).

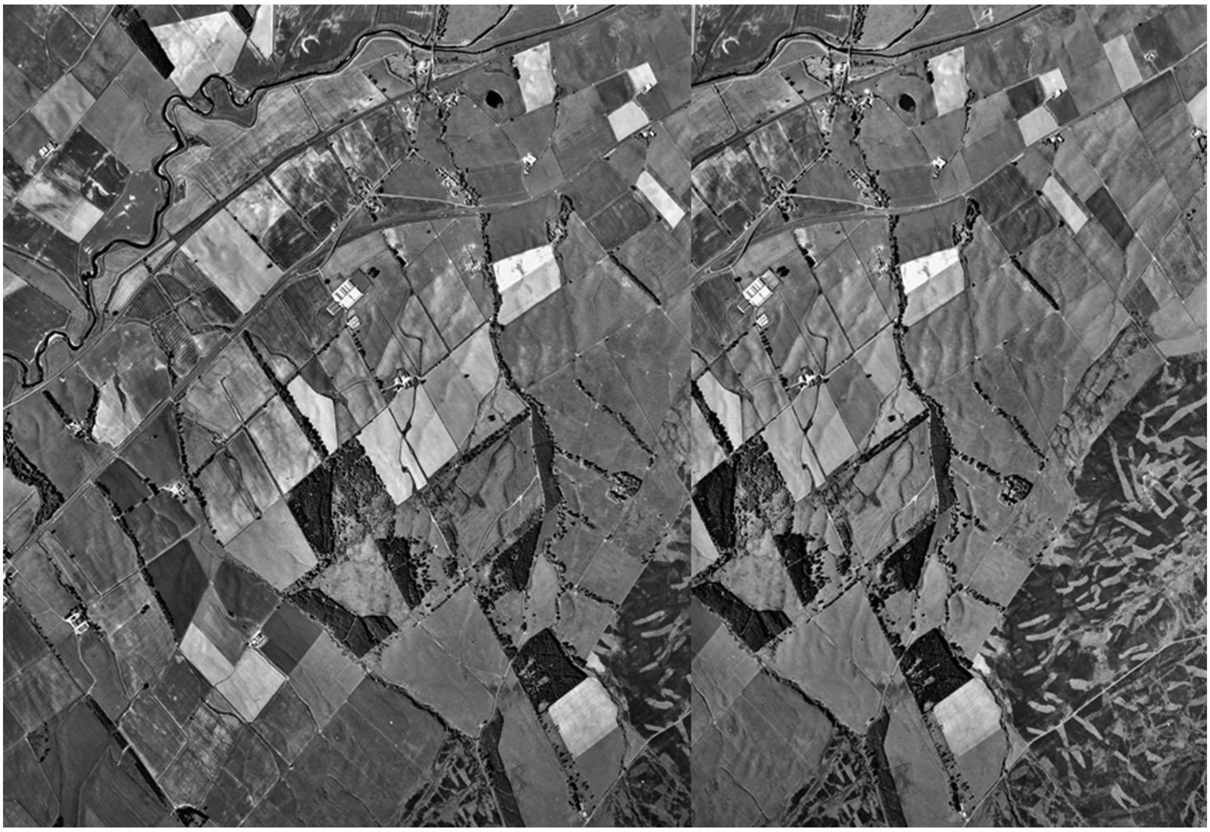

Figure 4. Aerial photograph stereopair of the meltwater channels on the south valley side of Strathallan below Sheriff Muir (copyright RCAHMS; photograph numbers ASS-511-88-169 & 170).

The glacifluvial landforms and deposits of the River Knaik valley are especially interesting as they form an extensive linear spread on the south valley wall contained within an inset sequence of dissected and pitted benches, the uppermost and most extensive of which descends from 267 m to 240 m OD (27 m) over a down valley distance of 2 km, or a 1:74 gradient (Figure 6). Considering that at least part of this tilt is likely due to westerly increasing postglacial glacioisostatic uplift, this is a very low gradient and one that would be typical of an ice-marginal stream. The inset nature of several terrace levels and their localized separation by intervening channels, in addition to their locally undulatory or pitted surfaces, indicate that they constitute kame terraces. The margin of the Knaik valley glacier lobe around which they were deposited is demarcated by an elongate body of morainic drift that lies at the lower ends of the uppermost lateral meltwater channels of the Strathallan lobe. Postglacial gullies incised through the landforms to the east of Glenlichorn reveal interbedded stratified sediments of well to very poorly sorted, gravels, sandy gravels and matrix-supported gravels. Clast-supported and massive to crudely stratified diamictons also occur towards the top of the sequences in many places. Very common are scour-and-fill sequences, distorted or gently folded bedding and normal faults. At the lower end of one meltwater channel in particular on the southern slopes of the lower Knaik valley, a large and well defined esker is visible within the glacifluvial infill of the lower slopes (Figure 7). This is typical of several features that were interpreted by Sissons (1961) as the deposits created by subglacial chutes and hence termed ‘subglacially engorged eskers’. This esker is important because it emerges from the lower end of the highest of the inset sequence of lateral meltwater channels on the northern valley side of Strathallan. This inset sequence of lateral meltwater channels wraps around the mountain spur that separates Strathallan from the Knaik valley, documenting the downwasting margin of the Strathallan glacier lobe and also revealing that it flowed into the lower end of the Knaik valley. The esker demonstrates that the meltwater descending the lateral channels plunged under or through ice in the valley bottom, likely the Knaik valley glacier lobe as it lies below the morainic drift associated with the kame terraces of that lobe. A further subglacially engorged esker was later emplaced by meltwater flowing out of the Knaik valley and under or through the lower margins of the Strathallan glacier lobe; it is located immediately south of the present River Knaik, where it separates the modern floodplain from the lower ends of the lateral meltwater channels (Figure 7). Exposures through this feature display interbedded stratified sediments of well to poorly sorted, gravels, sandy gravels and matrix-supported gravels often arranged in clinoforms or dipping bedded units and including partially scoured and infilled pockets of cross-stratified sands (Figure 8).

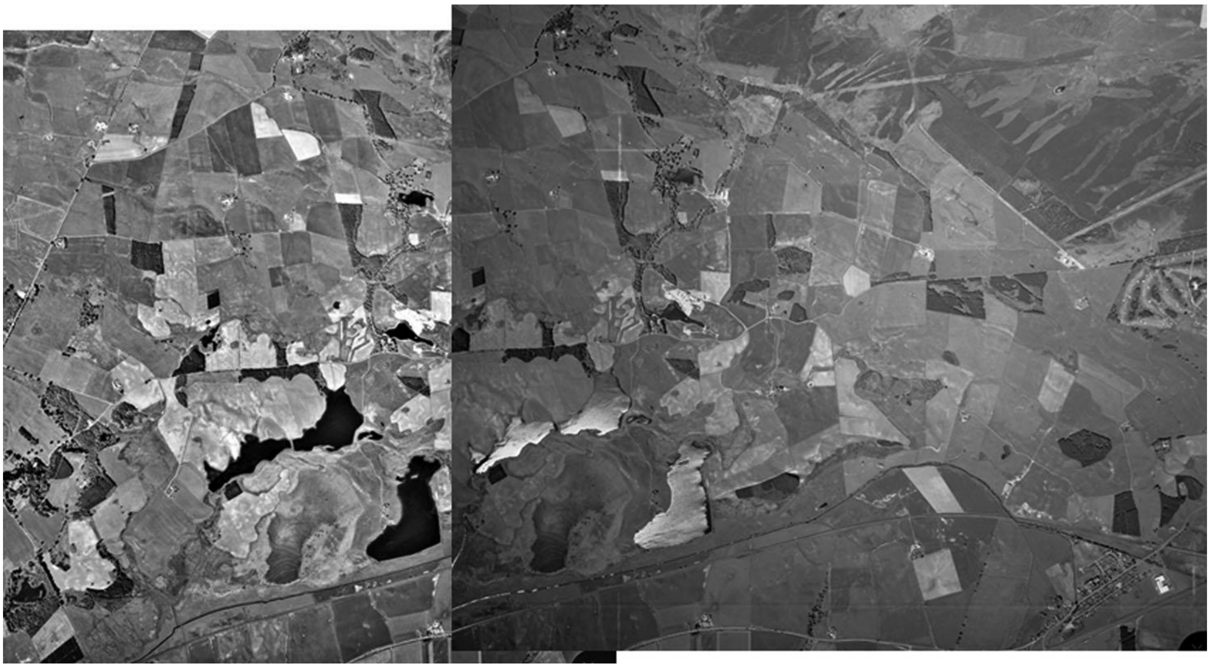

Figure 5. Aerial photograph stereopair of the eskers and kames in the vicinity of Gleneagles golf course, which is visible on the east side of the images (copyright RCAHMS; photograph numbers ASS-511-88-048 & 049).

Interpretation of the Landform Assemblage

When the complex landform assemblage of Strathallan and its tributary valleys is mapped out and viewed in the context of the regional and local topography (Figure 9), it becomes clear that a significant phase of glacifluvial activity is recorded in the glacial geomorphology. This is associated with the westward recession of a glacier lobe confined by the deglaciated uplands of the Ochil Hills in the south and Uamh Bheag/Knaik valley uplands in the north. The lobate margins of the glacier ice are clearly demarcated by the lateral meltwater channels developed first patchily above Auchterarder and then densely and more continuously on the slopes to the west of Gleneagles. The occupation of the Knaik valley by a separate, downwasting glacier lobe is documented by a short stretch of lateral moraine along the lower ends of the highest lateral meltwater channels on the north Strathallan valley slopes; an esker emanating from the highest of these channels and running downslope below the lateral moraine indicates that the two glacier lobes were coalescent and that the Strathallan lobe meltwater was at that time plunging down below the Knaik valley lobe. Further evidence for the Knaik valley lobe is the extensive, pitted and incised kame terrace that occupied the west valley side.

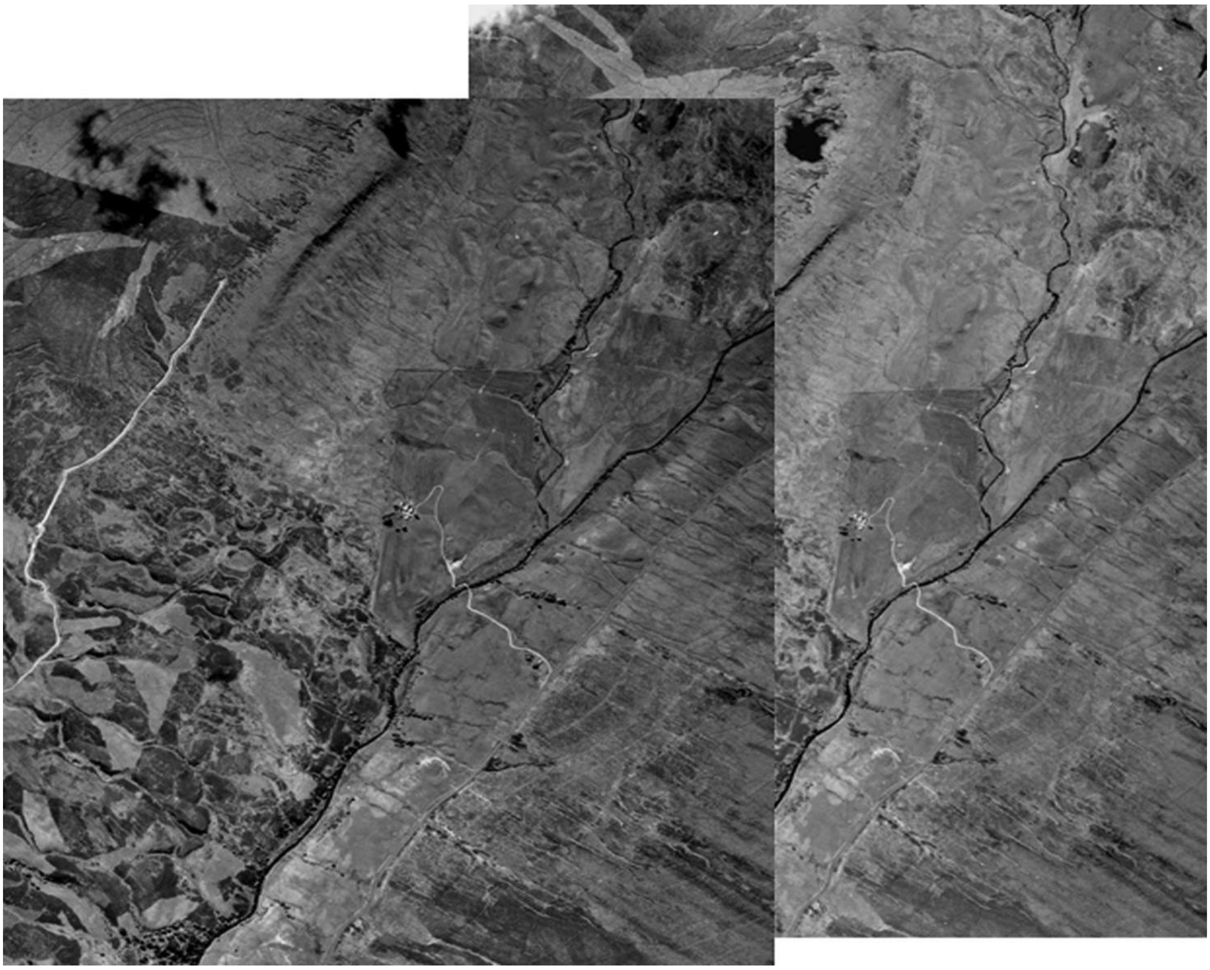

Figure 6. Aerial photograph stereopair of the kame terraces of the River Knaik valley (copyright RCAHMS; photograph numbers ASS-511-88-051 & 052). The farm of Glenlichorn and its access track, which lie on top of the terrace, are at the centre of the image.

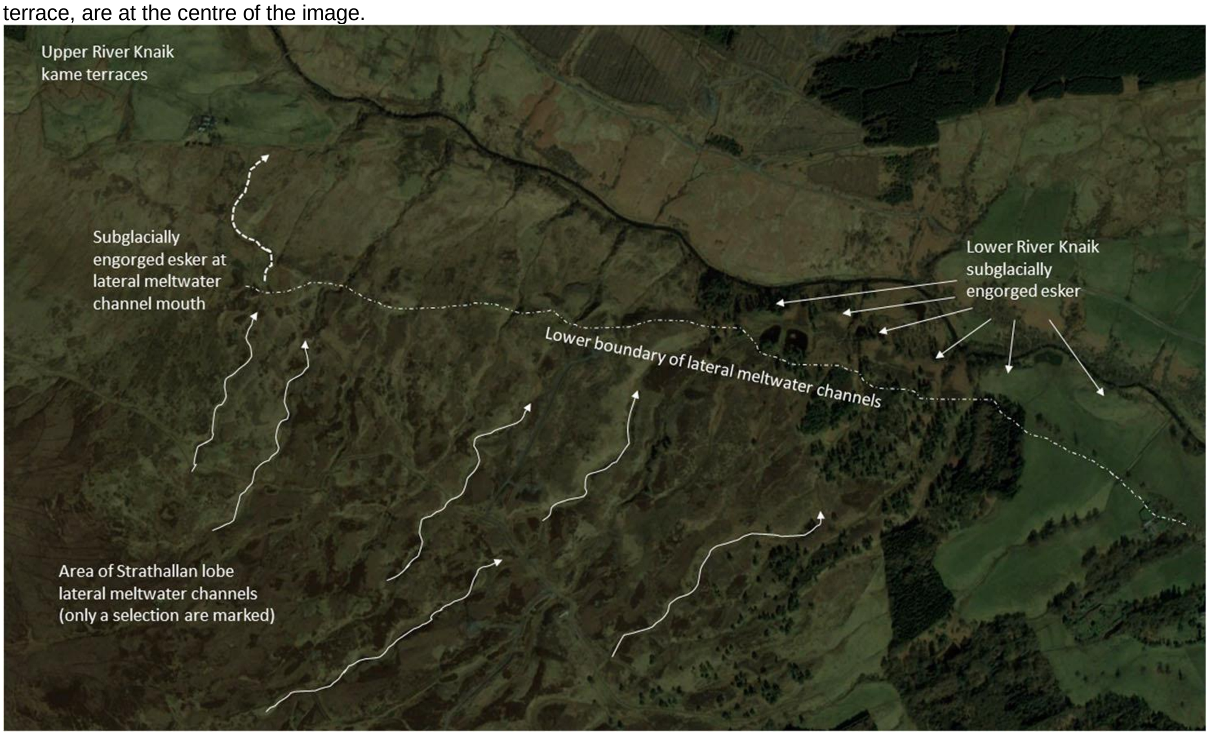

Figure 7. Google Earth image of the lower Knaik River valley and the lateral meltwater channels of the north Strathallan glacier lobe, showing the locations of the subglacially engorged eskers.

The abrupt change to slopes with no lateral meltwater channels, at the western end of Strathallan, on the hillslopes north of Dunblane, reveal that by the time the Strathallan lobe had receded that far west, marginal meltwater was no longer available in sufficient volume to incise and remove the drift cover and consequently emplace thick and extensive spreads of glacifluvial deposits in kame terraces and valley floor eskers and kame and kettle topography. The early phase of enhanced lateral meltwater incision around the Strathallan lobe must have been in response to restricted drainage access to the glacier bed and hence a predominantly cold-based thermal regime, at least around the upper margins of the lobe. Although the occurrence of eskers on the valley floor might appear to contradict this interpretation, tunnel infills (eskers) are not exclusively subglacial in origin and indeed many modern eskers, forming even in temperate glaciers, are emerging at present from englacial positions (Price 1969; Livingstone et al. 2010a, 2010b; Storrar et al. 2015). Hence the Strathallan valley floor eskers, at least in part, could have been let down onto the substrate from englacial tunnels. The subglacially engorged eskers of the area, as well as erosional chutes, indicate that lateral meltwater streams did indeed penetrate the glacier at least sub-marginally. Broader spreads of glacifluvial deposits in the form of flat-topped kames and kame terraces document the more advanced stages of glacier karst development when the infills of enlarged tunnel systems, collapsed cavities and ice-walled lakes and channels overwhelmed the glacier snout. A gradual change in the nature of glacial meltwater channel incision appears to be documented in the pattern of channel types, as classified in Figure 9. A similar spatial and temporal evolution of drainage styles based upon meltwater channel types has been documented in other parts of the British Isles (Greenwood et al. 2007; Livingstone et al. 2010a, 2010b) and is characterized by inset sequences of marginal, sub-marginal and subglacial channels which reflect the changing nature of the glacial hydrology and glacier thermal regime. This features the development of cold-based margins at the more advanced (topographically confined) stages of ice sheet recession, as marked by lateral/marginal meltwater channels (light blue on Figure 9), which then grade downslope/temporally into sub-marginal (green) and then subglacial (dark blue) channels as the thermal regime warms. Marginal or lateral channels are distinctive in that they are orientated almost contour parallel and rarely link to one another, characteristics that indicate meltwater drainage along a predominantly cold-based and receding glacier margin (Dyke 1993). Sub-marginal channels are those that show similarities to lateral channels but which trend downslope and at less oblique angles to slope contours (i.e. at steeper gradients), often ending in chutes or containing chutes along their lengths. Subglacial channels are typically relatively continuous and exhibit undulatory long profiles, often forming anastomosing networks of broadly parallel channels and associated with valley floor eskers. Subglacial channels and eskers in Strathallan record the more advanced stages of glacier snout downwasting and glacier karst enlargement and infilling with sands and gravels.

Figure 8. Exposure through the largely poorly sorted, gravel and sandy gravel clinoforms infilling a scour in underlying cross-stratified sands in an exposure through the lower River Knaik subglacially engorged esker.

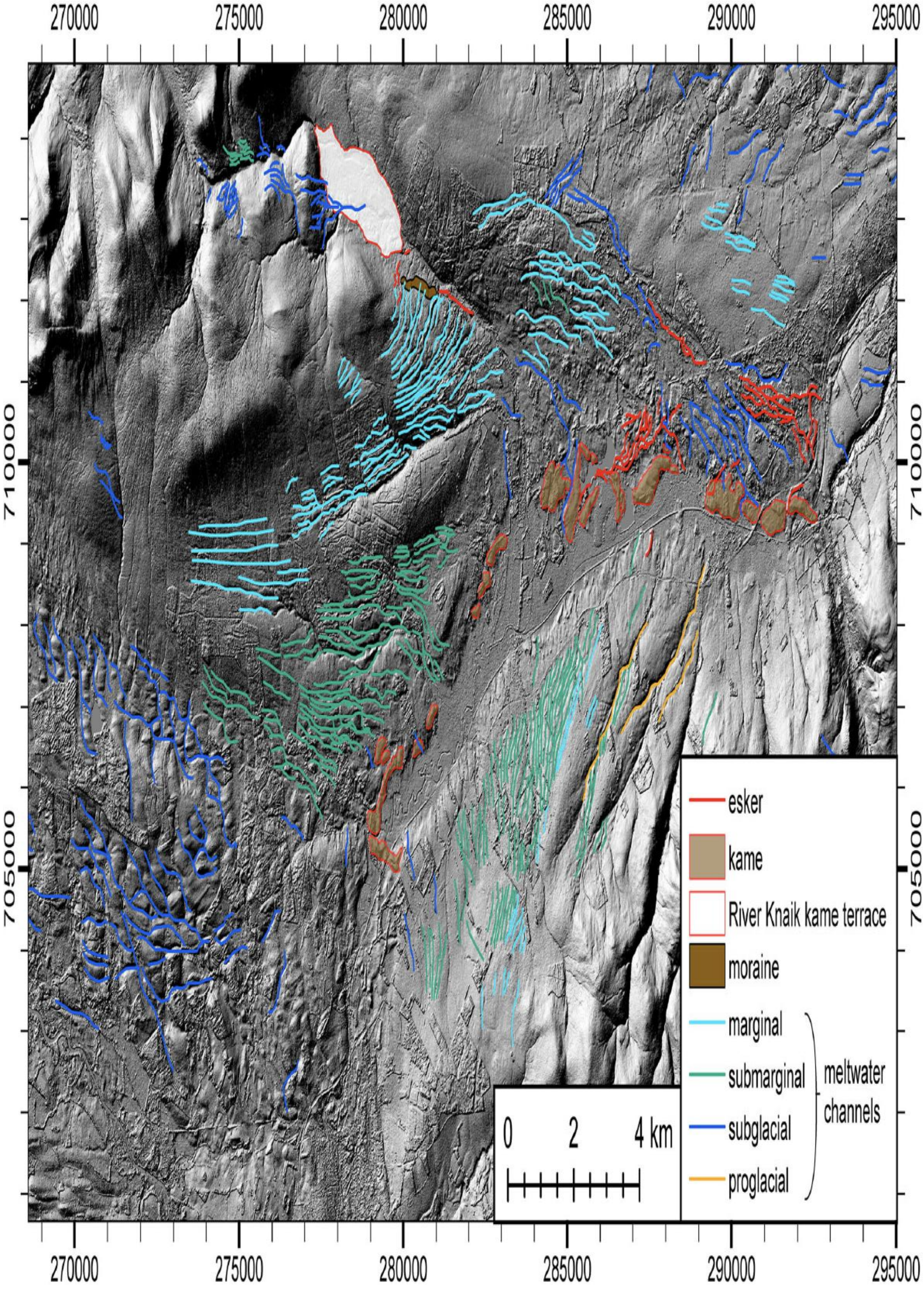

Figure 9. Map of the glacifluvial landforms in Strathallan and the River Knaik valley annotated on NEXTMap digital elevation model (NEXTMap Britain data from Intermap technologies Inc. provided courtesy of NERC). Note that only the most prominent landforms are marked and hence some of the more subtle features, for example, smaller kame mounds, are not highlighted.

Conclusion

A remarkable concentration of erosional and depositional glacifluvial landforms and sediments in Strathallan and the tributary River Knaik valley documents a phase of intense meltwater production during the overall recession of the last ice sheet in the region. The meltwater was derived from melting on a topographically confined glacier lobe that was receding towards the west, out of the Strathallan valley. During the early stages of meltwater drainage, channels were incised ice-marginally, indicative of the derivation of runoff from glacier surface snow and ice melt, and consequently strongly diagnostic of predominantly cold-based glacier margins. A gradual change downslope from lateral channels to sub-marginal and eventually subglacial channels, records a switch from supraglacial to increasingly englacial and subglacial drainage and the concomitant development of glacier karst during glacier snout downwasting. This glacier karst phase is documented by the valley floor networks of kames, kame terraces and eskers. Throughout the period of glacifluvial landform development the proglacial routing of meltwater was over the Strathallan/Strathearn watershed via the downcutting gorge of Kincardine Glen.

Access Information

All of the features described here can be viewed from the numerous roads in the area. The River Knaik valley features can be viewed more closely on foot but permission should be first sought from the farm at Glenlichorn. The higher altitude meltwater channels above Braco Castle are on open moorland and can be accessed on foot, again via Glenlichorn. Golfing geomorphologists can appreciate the prominent esker ridges of Strathallan by playing the Gleneagles or Auchterarder courses. The landforms are covered by Ordnance Survey 1:50,000 scale Landranger maps 57 and 58.

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